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# THE ATMOSPHERE OF MARS IN THE LANDING AREA OF THE DESCENT APPARATUS OF MARS-6 (PRELIMINARY RESULTS)

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16. Abstract

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THE ATMOSPHERE OF MARS IN THE LANDS AREA
OF THE DESCENT APPARATUS OF MARS-6
(PRELIMINARY RESULTS)

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On 12 March 1974, the Mars-6 automatic interplanetary /1*
station (AIS), launched 5 August 1973, reached the vicinity of Mars, and after a final course correction, the descent apparatus (DA) was released. The final correction was made automatically by means of the on-board astronavigation system. The engine of the descent apparatus shifted it into a trajectory terminating on the planet's surface. After that, a programmed turn was executed to provide the necessary angle of attack for an entry into the atmopshere. The orbital apparatus (OA), also after performing a programmed rotation, continued its flight in a heliocentric orbit, passing within about 1600 km from the surface of Mars.

The design of the Mars-6 DA and its landing system are generally similar to the Mars-3 DA described in [1, 2]. The apparatus was equipped with a heat-protective aerodynamic cone, protecting the DA from the high temperatures developed in the area of the shock wave in front of the apparatus and slowing it from its hypersonic velocity upon entry to the atmosphere to a speed of about Mach 3.5, at which time the parachute system was activated. The parachute system was a multistage system, with a pilot chute and a main chute (initially reefed). The on-board automatic equipment, in combination with the radio altimeter (RA), a time programming device and acceleration sensors, generated the necessary commands, including the command to

*Numbers in the margin indicate pagination in the foreign text.

+Principal investigator

switch on the soft landing motor and release the parachute. /2
The descent of the DA is diagrammed in Figure 1.

The program of motion of the DA in the atmosphere consists of the following main elements:

-- when the DA enters the atmosphere, when a longitudinal g load of $n_x = -2$ is reached, the command is given to start the solid fueled motors which stop the rotation of the DA around its longitudinal axis;

-- when a speed of about Mach 3.5 is reached, the command is given to release the pilot parachute, followed by the main parachute, reefed to 0.4 ($S_{total} = 90$ m$^2$, $C_x \simeq 1.0$-$1.2$);

---after 12 seconds, the main parachute opens, after two more seconds the cone is dropped and after 5 seconds the RA is turned on;

-- after a certain time, the soft landing engines are extended.

The total weight of the system carried by the parachute $G_{DA} = 635$ kg.

Information from the DA during the time of aerodynamic braking and descent on the parachute was relayed through the Mars-6 OA to Earth. In the immediate vicinity of the surface, at a velocity of $V_{DA} = 60$-$65$ m/sec, radio communidation with the descent apparatus was interrupted. The DA reached the surface of Mars in the area of Margaritifer Sinus, in a region with nominal coordinates of 23.9° S, 19.5° W.

Combined analysis of the information transmitted by the DA indicates that the descent was nominal right up to 0-2 sec before touchdown and yields some information on the parameters of the atmosphere of Mars in the region of the descent from the surface to an altitude of about 80 km, satisfying all measured data. The initial information includes data from measurements of the mutual velocity of the OA and DA $V_D(t)$, measurements of the g loads $n_x(t)$, measurements of the atmospheric pressure

P(t) and altitude above the surface h(t). The models produced by measurement were subsequently compared with models used in the plan calculations. /3

In order to provide a check of the motion of the DA and to estimate the parameters of the atmosphere on the basis of the results of the actual descent of the Mars-6 spacecraft, the mutual velocity of the OA and DA was measured. After receipt by the OA, amplification and shifting to the low-frequency range, the carrier signal from the DA was relayed to Earth over the OA-Earth radio link.

On Earth, the parameters of the relayed signal were continually measured, it was recorded on a wide-band analog tape recorder and, after analog-to-code conversion, on digital tape recorders. The use of highly stable temperature-controlled oscillators on the OA and DA allowed the frequency of the relayed signal to be used to determine the difference in velocities of DA and OA in the projection on the DA-OA line.(Figure 2). Here $V_{D(t)}$ is the mutual ray velocity. Due to aging of the crystal resonator of the DA during the flight, the mutual velocity was determined with an accuracy determined by a constant component. The performance of such measurements represented a very complex task due to the low signal/noise ratio resulting from the limited power of the on-board transmitters and the very rapid change in Doppler frequency as the DA decelerated in the atmopshere.

The results of measurements of the velocity are shown in Figures 3a and b. Measurements of velocity were performed for about 25 minutes over the flight sector preceding entry of the DA into the atmosphere and for about an additional 200 sec during the descent in the atmosphere down to the surface. During this stage, the data produced by the trajectory measurement system of the Center for Long Range Space Communidations were used. During the sector of rapid velocity change (from the moment of restoration of communications to 12:08:50), measurements were performed using the recording of signal frequency on a visual recording /4 device. These data are preliminary in nature and relate to a time of about ±3 sec (horizontal line on Figure 3).

As we can see, the preatmospheric section shows a comparatively slow increase in velocity; measurements during this section were used to refine the trajectory of the DA. At an altitude of 68 km, the concentration of plasma around the DA exceeded the critical value, causing a loss of communication. Communication was restored in about 80 seconds, when the spacecraft reached an altitude of 21 km. The first derivative of velocity at the moment when communication was restored was 45 $m/sec^2$. The subsequent measurement sector was characterized by a sharp change in $V_{D(t)}$ due to the deceleration of the DA in the atmosphere. The section up to 12:08:32 corresponds to braking by the aerodynamic cone, while the bend at 12:08:32 (altitude 11.6 km) corresponds to the sudden increase in braking as the parachute system opened. The "minimum" in the measurements of mutual velocity at 12:09:04 corresponds not to an actual minimum in DA velocity, but rather the moment when the derivative of the DA velocity in its projection on the DA-OA line becomes equal to the corresponding projection of the gravitational acceleration of the OA. During its subsequent descent, the DA became quasistationary, and the change in velocity was relative slow, since the main portion of the change in mutual velocity resulted from the movement of the orbital apparatus.

The DA-OA sighting line during the quasistable descent sector was inclined to the local horizon of the DA at an angle of about 35°, while its projection was directed almost along a latitude line. Due to this, the zonal wind component is included in the quasistable descent sector with a coefficient of near unit (see [3]).

The analysis of the Doppler measurements performed at the time, in comparison to the DA descent version calculated before the landing showed that:

-- the DA entered the atmosphere at a moment near the time /5 calculated for an entry angle of about 11.5°;

-- the parachute system functioned normally (the bend on the velocity curve at 12:08:32 corresponds to the release of the parachute, while the lack of variations in velocity indicates a smooth descent through the atmosphere);

-- the time of descent of the spacecraft on the parachute for an entry angle of about 11.5° corresponds to an atmosphere with a surface pressure of about 6 mbar.

The Doppler measurement data were used to determine also the variations in ray velocity of the DA in the quasistable descent sector. Noticeable variations with amplitudes of 2-4 m/sec and periods of 10-20 sec were observed up to about 12:09:50 and were apparently a result of oscillations in the parachute-DA system following perturbation upon entry and unreefing of the parachute and at the moment of release. Subsequently, oscillations with amplitudes of over 2 m/sec were not observed, and the course of the measurement curve of velocity remained near the calculated course. This indicates, first of all, a smooth spacecraft descent without strong swinging (although we should recall that only one velocity component was measured) and, secondly, slight variation in wind speed, including the vertical component (time constant of parachute-DA system is about 15 sec). The near nominal nature of the change in mutual velocity also indicates a slight (less than 5-7 m/sec) change in wind speed at altitudes of 0 to 7.5 km.

The axial g loads were measured during the preparachute aerodynamic braking sector in the atmosphere of Mars in order to determine the density of the atmosphere and trace the dynamics of motion of the apparatus. The change in g load as a function of time $n_x(t)$ is shown in Figure 4.

The g load measurement system consisted of an inertial sensor with a potentiometer and flip-flop memory registers. The system performs the following logic functions:

-- recording of moments of attainment of preselected accel-

acceleration levels; /6

-- determination of the maximum value of g loads and corresponding moments in time;

-- storage of information until the beginning of operation of the DA telemetry system.

Considering the systematic temperature and random errors of the sensor, the values of axial g loads for which times were recorded were as follows:

-- on the ascending branch, 4.2 ± 0.25 and 9.75 ± 0.25 ($n_{x2}$, $n_{x3}$)

-- on the descending branch, 4.2 ± 0.25 ($n_{x4}$).

The summary error in measurement of the maximum g load is ±1.2% of the range of measurement, corresponding to ±0.45 acceleration units, and including the methodological error (±1%) and the error of the sensor (0.7%).

The measured value of maximum axial acceleration was $n_{x\ max} = 9.8^{+0.44}_{-0.3}$. The lower boundary was determined by the previous level of acceleration on the ascending branch 9.75 ± 0.25. The time to fixed levels of acceleration and to the moment of achievement of its maximum value were calculated from the level $n_{x1} = 2^{+0.25}_{-0}$ on the ascending branch of the curve (Figure 4). With a smooth maximum on the curve of axial acceleration, the time of achivement of $n_{x\ max}$ corresponds to the left boundary of the interval in which the maximum value is reached. The measured integral times were:

-- in the ascending branch $t_{n_{x2}} - t_{n_{x1}} = 9.2 \pm 0.25$ sec and $t_{n_{x3}} - t_{n_{x1}} = 23.8 \pm 0.25$ sec;

-- in the descending branch $t_{n_{x4}} - t_{n_{x1}} = 57.2 \pm 0.5$ sec;

-- to the maximum acceleration $t_{n_{x\ max}} - t_{n_{x1}} = (28.6 \pm 0.5)$ sec.

The value of maximum axial acceleration found can be used first of all to determine the level $n_{x_5} = (0.14 \pm 0.01)\ n_{x_{max}} =$

= 1.37 ±0.15, used to actuate the parachute system of the DA. /7
On Figure 4, the solid line shows the design dependence of acceleration on time for the conditions of entry of the DA of the Mars-6 spacecraft and the model of the atmsophere of Mars with surface parameters $P_0$ = 5 mb, $T_0$ = 200 K with a tropopause altitude $h_t$ = 12 km. The level of $n_{x1}$ = 2 was also used as the beginning of the reading. As we can see, the difference between measured and calculated values for the limiting measurement errors in this case falls within limits of one sec.

To correlate the results produced to the instantaneous time, the moment of interruption of radio communication at the surface of Mars was used. The processing performed to date yields an estimate of this moment of 12:11:05 Moscow time (Figure 3). Since the duration of transmission of telemetry information during the parachute section was 149.2 sec, the time of operation of the parachute system of the DA 2.4 sec and the time of selection of $n_{x5}$ 1.5 sec, we can estimate the passage through g load level $n_{x5}$ on the descending branch of the curve as 12:08:32, which agrees well with the break point on the curve of $V_D(t)$ (Figure 3). The characteristics of the Martian stratosphere were estimated using a method presented in [4]. On the assumption of an isothermal stratosphere over the measurement section, the temperature range T = 120-190 K was studied, with a corresponding logarithmic density grandient $\beta$ = 0.1-0.165 $km^{-1}$. At the lower boundary of the isothermal layer $h_t$, the density was assumed to be $\rho_{h_t}$ = = $(4-7)\cdot 10^{-3}$ $kg/m^3$. As a result of solution of the system of equations of motion of the DA in the atmosphere, values of time intervals and maximum acceleration were calculated within the fixed range of temperature of the stratosphere (Figure 5a, b), as well as the intervals of time from the entry into the atmosphere to the level $n_{x1}$ = 2 and from the level $n_{x4}$ to $n_{x5}$ on the descending branch of the curve (Figure 5c). The results of /8
calculations were compared with the measured values of these quantities. In the overlapping ranges of parameters common to

all measurements, the mean stratosphere temperature $T = 144^{+8}_{-6}$ K and respectively $\beta = 0.137^{+0.006}_{-0.007}$ km$^{-1}$. The nominal values of measured parameters on the ascending branch (Figure 5a, b, dotted line) correspond to $T = 152^{+6}_{-8}$ K and $\beta = 0.130^{+0.005}_{-0.006}$ km$^{-1}$, on the descending branch $T = 138^{+6}_{-8}$ K and $\beta = 143^{+0.003}_{-0.006}$ km$^{-1}$. The temperature $T = 144^{+8}_{-6}$ K corresponds to $\rho_{h_t} = (5.1 \pm 0.4 \cdot 10^{-3}$ km) (Figure 6a, b). In the altitude area $h > h_t$, the density is determined from the exponential dependence $\rho = \rho_{h_t} e^{-\beta(h-h_t)}$.

The mean temperature T = 144 K (Figure 5a, b) corresponds to the following values of measured quantities:

-- in the ascending branch $\Delta t = 8.95$ sec and $n_x = 4.45$; $\Delta t = 23.55$ sec and $n_x = 9.75$;

-- on the descending branch $\Delta t = 57.7$ sec and $n_x = 9.75$;

-- $n_{x\ max} = 10.2$; $\Delta t_{n_{x\ max}} = 28.4$ sec.

If we utilize the model of the atmosphere presented above above the $h_t$ level, then, as follows from Figure 6c in the range of altitudes where axial g loads were measured, $h_{n_{x2}} = 41.4^{+3}$ km; $h_{n_{x4}} = 15.6^{-1.6}$km; $h_{n_{x\ max}} = 23^{+2.2}_{-1.8}$ km.

Restoration of the picture of motion during the deceleration sector allows us to refine the ballistic prediction of the time of arrival of the DA at the arbitrary upper boundary of the atmosphere of Mars and determine the duration of the preparachute descent sector. Calculations show that the entry angle of 12°09' (ballistic prediction) is near the actual angle. With angles of less than 11.5° or more than 12.5°, the measured and calculated time intervals for passage through the various values of $n_x$ disagree, which is difficult to correlate with the usual assumed parameters of the stratosphere of Mars. However, we should note that the isoterhaml distribution of temperature in the stratosphere corresponds to the limiting values of measured time /9
intervals and accelerations. Therefore, we can assume that the profile of temperature in this area differs somewhat from isothermal, with temperature gradients in some sectors determined

by the limiting values of the approximating isotherms $T = 138^{+6}_{-3}$ K and $152^{+6}_{-9}$ K.

To allow direct determination of the parameters of the atmosphere, the Mars-6 DA carried devices for measurement of its temperature and pressure and a mass spectrometer. Results of analysis of the telemetry information concerning the operation of the mass spectrometer are reported by Istomin et al. [5]. The P and T sensors were membrane manometers and resistance thermometers. The sensing element of the resistance thermometers was a platinum wire 50 mm in diameter with bifilar winding in the form of a rectangular frame. The frame was suspended on strips of mylar film to a pressboard frame.

The range of temperatures measured during the descent sector was from -150 to +50° C, with a standard (mean square) error of measurement of ±5% of full scale (according to laboratory calibration under conditions similar to those encountered).

The pressure sensor, designed for a measurement range of 0 to 12 mbar with a standard (mean square) measurement error of ±5% of the full scale in the temperature range from -20 to +50° C utilized a metal membrane 1.8 cm in diameter and 100 μ thick and a capacitive sensing element. The working volume of the sensor was evacuated on the DA side. The possible uncontrolled zero drift was not over 1 mbar.

The pressure and temperature sensors were designed primarily to perform measurements on the surface of Mars; therefore, they were not to be exposed until after the landing and adjustment of the DA to its operating state. Measurements using some of the /10 parachute descent sector were supplementary in nature. This concerns primarily the temperature, since direct measurement in a stream of rarefied gas, considering the possible influence of hot streams from the boundary layer and irradiation of elements of the spacecraft structure heated during the aerodynamic braking sector, might be significantly in error, and correction is quite difficult. The data from temperature measurements can be further analyzed considering modeling results.

The results of measurements of pressure and altitude over the surface in the area of descent of the spacecraft as a function of time are shown in Figure 7. Since the P sensor was carried in the tail portion of the spacecraft, the measurement data were corrected to consider the difference of the full head from the static pressure using the dependence

$$P = P_{meas}\left(1 + \frac{K - 1}{2} M^2\right)^{-K/K-1},$$

where $K = C_p/C_v$ is the ratio of heat capacities at constant pressure and constant volume for $CO_2$;

M is the Mach number ($M < 1$ over the entire measurement sector). The vertical lines indicate the measurement errors, the arrow along the ordinate shows the possible zero drift, which might cause an increase in the total (random plus systematic) error of measurement to approximately double its value. Approximation by a second-power polynomial quite satisfactorily describes the initial fields of measured points P(t) and h(t). At the end of the measurement at the surface of the planet in the area where the apparatus landed, the pressure was $P = 6.1 \pm 0.5$ mbar.

Figure 8a shows the change in pressure during the time of parachute descent as a function of altitude. Here also we show the logarithmic pressure gradient and an estimate of the temperature of the atmosphere, produced using the obvious relationship: $\frac{d \ln P}{dh} = -\frac{1}{H}$, where $H = \frac{RT}{\mu g}$.

In this (isothermal here H = const) approximation, the mean temperature of the troposphere of Mars is 228 ± 10 K. Considering the errors in determination of P, an attempt to produce the dependence T(h) in the approximation $H \neq$ const is hardly justified. Figure 8b shows the dependence of changes of density on altitude, calculated on the basis of the hydrostatic equation and the equation of a quasi-even descent on the parachute for /11 various values of $C_x$. The best agreement with the calculated values using the equation for hydrostatic equillibrium for measured values of P(h) occurs for $C_x \approx 0.95$.

In addition to the separate analysis of measurements, the results of which are presented above, an attempt was made at combined utilization of the measurements of $V_D(t)$, h(t), P(t) and $n_x(t)$ for most reliable determination of the parameters of the Martian atmosphere. Performance of this task is a very difficult problem, involving a large number of influencing factors, related not only to the atmosphere itself, but also to inaccuracies in determination of the aerodynamic characteristics of the apparatus with its complex functioning plan, inaccuracies in determination of the trajectory of the DA and OA, etc. The task was performed by multistage variation of parameters of the atmosphere, as well as variation of the flight trajectory of the DA until all the measurements were satisfied.

It was assumed that the atmosphere of Mars consists of two sections -- the convective section with linear change in temperature with gradient $\gamma$ and an isothermal section beginning at latitutde $h_t$. The altitude was related to the level with pressure 6.1 mb, which at the latitude of the landing point (-23.9° S) according to radio occultation studies [6], corresponds to a distance of 3392 km from the center of Mars. The variable parameters of the atmosphere were: temperature near the surface $T_0$, height of tropopause $h_t$, temperature gradient $\gamma$, which automatically led to variations in the temperature of the isothermal section $T_x = T_0 - \gamma h_t$. The primary variable parameter in the trajectory used was the normal component of velocity of the DA at the moment when the spacecraft received its braking impulse (a distance of about 45000 km from the center of Mars). It was this component which, through variation of the angle of entry, had the greatest influence on the movement of the DA. During integration of the equations of motion, the compression of the gravitational field of Mars [7] and combustion of the aerodynamic cone were con- /12 considered; it was further assumed that all motion occurred at 0 angle of attack, the atmosphere consists of pure $CO_2$, and the windspeed throughout the entire descent was assumed equal to 0.

The solution had as its task the production of agreement between calculated curves for $P(t)$, $n_x(t)$, $h(t)$ and $V_D(t)$ with measured curves, adjusted to current time. It should be noted that the dynamic and trajectory parameters were sensitive to density; therefore, estimates of temperature distribution on their basis can be performed only with limited accuracy.

As a result of the calculations performed, it was found that at the current stage of analysis, the entire set of measurements availableis best satisfied by an atmosphere with the following parameters: $T_0$ = 230 K; $T_u$ = 155K, $\gamma$ = 2.5°/km, $h_t \leq$ 30 km, meaning that the point of contact with the surface lies at an altitude of 400 m above the relative level P = 6.1 mb, so that the calculated pressure at the surface is $P_0$ = 5.9 mb. The vertical velocity of the apparatus at the surface was 61 m/sec. The results of calculation are presented in Figure 9. Along with the calculated values, we show the measured dependences of $P(t)$, $h(t)$, $V_D(t)$ and $n_x(t)$ for this model. The difference between the calculated altitude and the measured altitude (in addition to the systematic deviation of about 400 m, related to the local relief) over the entire section is 50-100m, the deviation of pressure $\Delta p < 0.2$ mbar, of acceleration $\Delta n_x < 0.4$ g, of velocity $\Delta V_{DA} < \pm 7$ m/sec. The calculated time of operation of the parachute system and loss of signal upon entry into the atmpsphere coincide to the measured values with an accuracy of about 3 sec. The calculated, somewhat lower values of acceleration, in addition to measurement errors, may be explained by a slightly lower temperature (about 145 K) of the stratosphere, as was indicated by separate analysis of the measurement data of $n_x(t)$.

At present, it is difficult to make an estimate of the accuracy of determination of the parameters of the atmosphere corresponding to the model presented in Figure 10. Analysis of various versions shows that the accuracy of estimation of temperature at the surface is $\Delta T_0 \approx \pm 20$ K, of pressure $\pm 0.5$ mb, of temperature above the level of the tropopause $\Delta T_u \approx \pm 10$ K, of windspeed $\Delta V \approx \pm 10$ m/sec.

The data of remote measurements of the parameters of the atmosphere by the Mariner-4, 6, 7, 9 and Mars 2-7 spacecraft generally agree well with the direct measurements presented and the estimates produced by analysis of the descent. The data of measurements of Mars-5 in a region adjacent to the area of landing of Mars-6 show that the atmospheric pressure, determined by absorption in the bands of $CO_2$ is 5-6 mbar [8]. For comparison, Figure 10 also shows the altitude profiles of atmospheric parameters according to the working models of the atmosphere of Mars [9, 10].

The results of combined analysis also yield certain preliminary estimates on the dynamics of the Martian atmosphere. The agreement of calculated and measured values of the mutual velocity shows that over the last 100 sec of descent, i.e., at 0-7.5 km altitude, the windspeed was apparently near 0.

We note here that a variation in atmosphere parameters (as well as OA trajectory parameters) leads to near parallel shifts in mutual velocity over the section of quasistable descent. Therefore, agreement between calculated and measured quantities /14
could also be attained with other atmospheric parameters, by introducing a wind with a velocity near constant with changing altitude.

However, considering the good agreement of calculated and measured (by radio altimeter) descent rates, it is imporbable that the value of the constant component of windspeed exceeded about 10 m/sec, or that the change of wind with altitude was over 5-7 m/sec.

The results of analysis of the descent of the Mars-6 APS descent apparatus in the atmosphere of Mars are preliminary in nature and require further refinement.

The authors would like to take this opportunity to express their deep gratitude to their many colleagues who participated in the preparation and performance of this difficult experiment.

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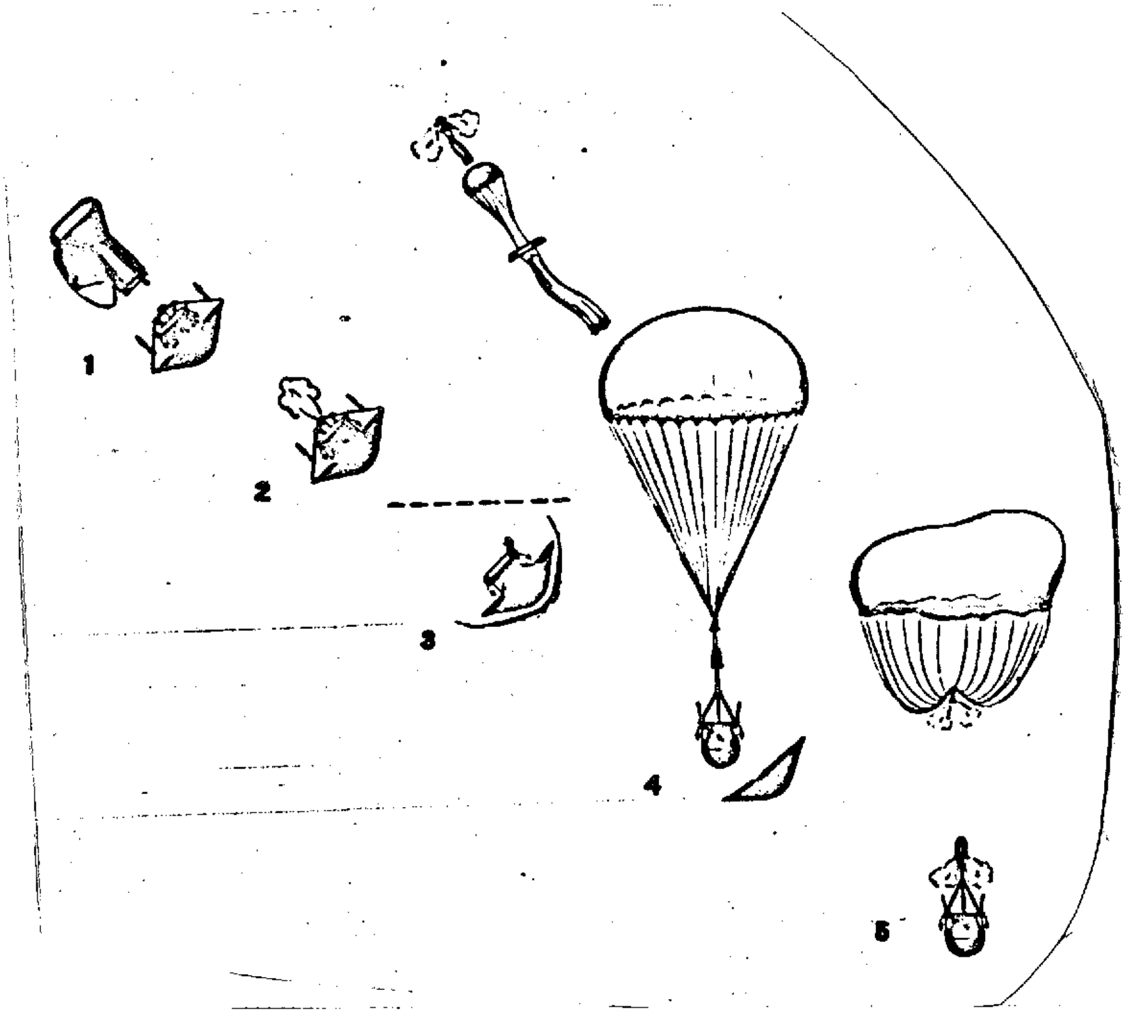



Figure 1. Diagram of Descent of DA in Atmosphere of Mars. 1, Separation of DA; 2, Firing of DA Engine; 3, Aerodynamic Braking; 4, Parachute Descent [5 not given -- tr.]

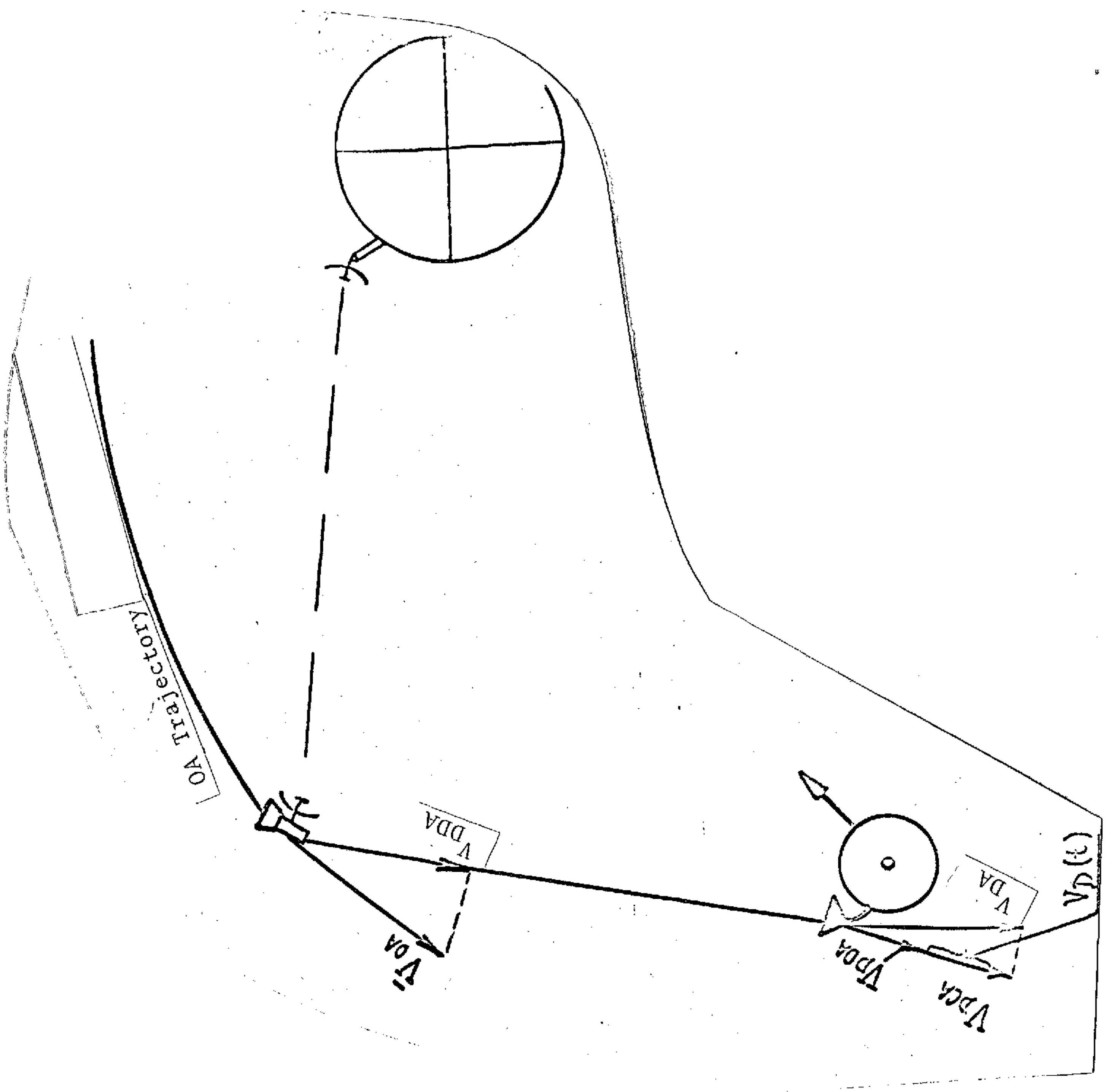



Figure 2. Plan of Measurement of Mutual Velocity of DA and OA

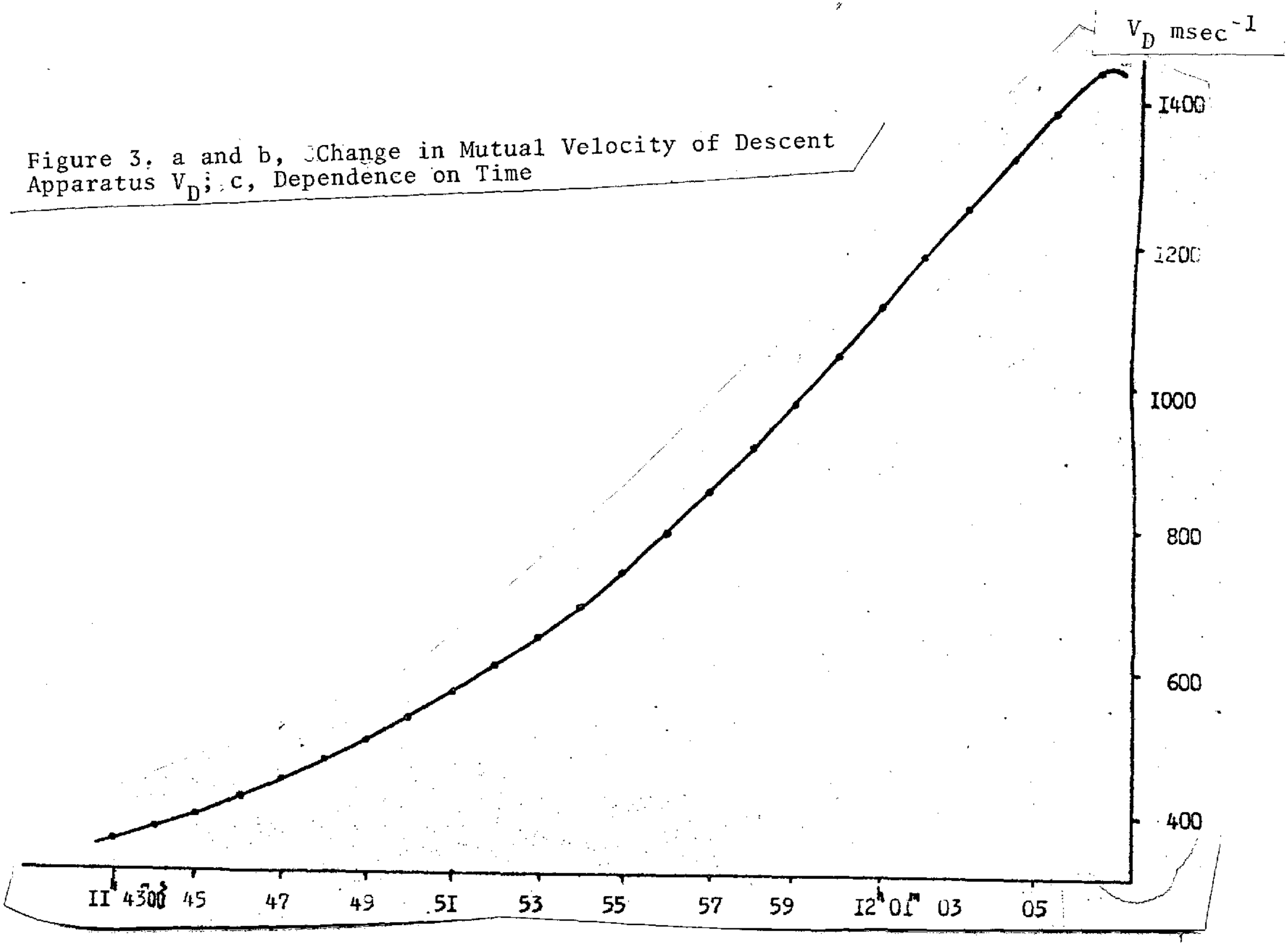
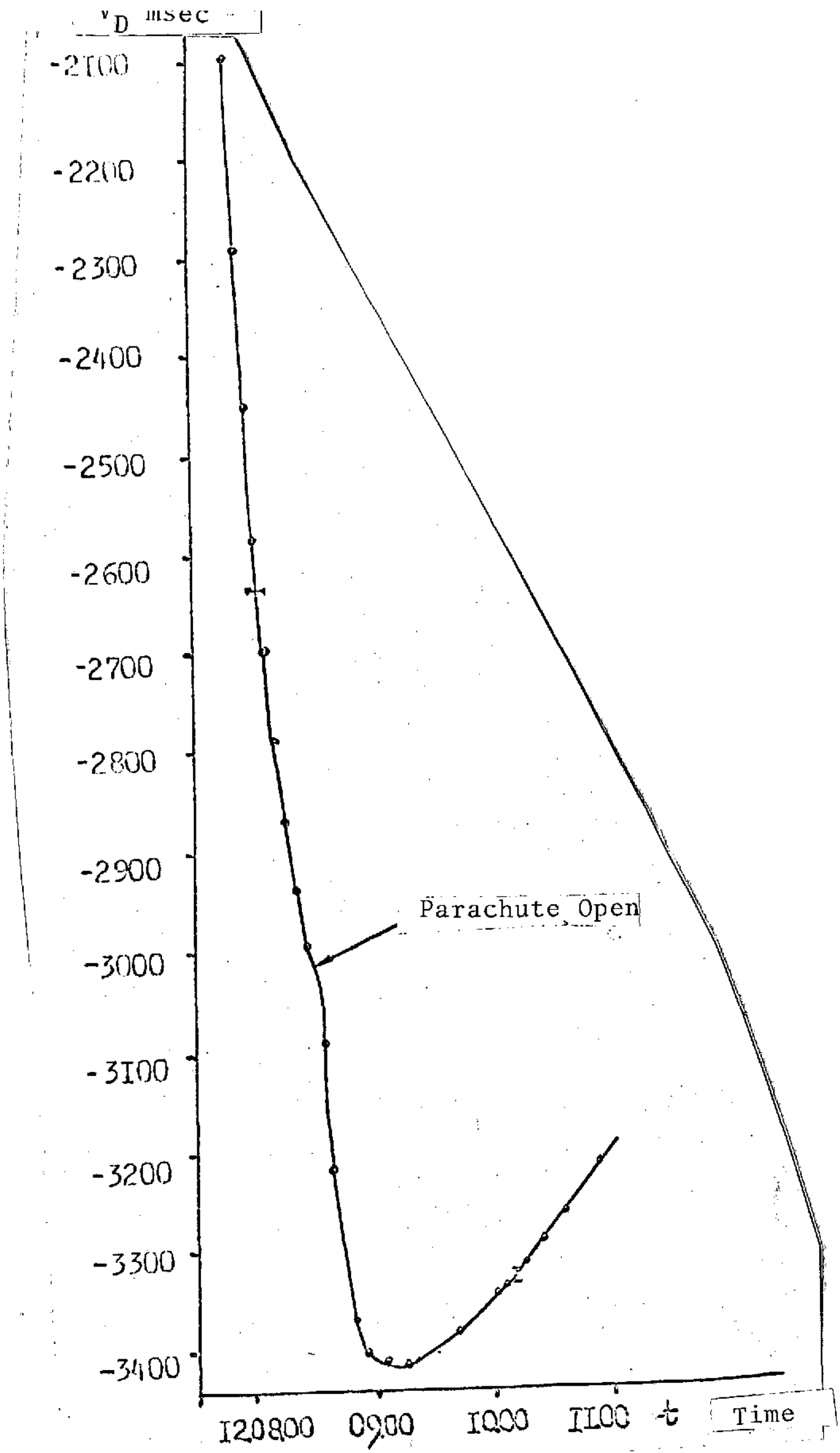



Figure 3. a and b, Change in Mutual Velocity of Descent Apparatus $V_D$; c, Dependence on Time



$v_D$ msec
-2100
-2200
-2300
-2400
-2500
-2600
-2700
-2800
-2900
-3000
-3100
-3200
-3300
-3400
Parachute Open
120800
0900
1000
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Time

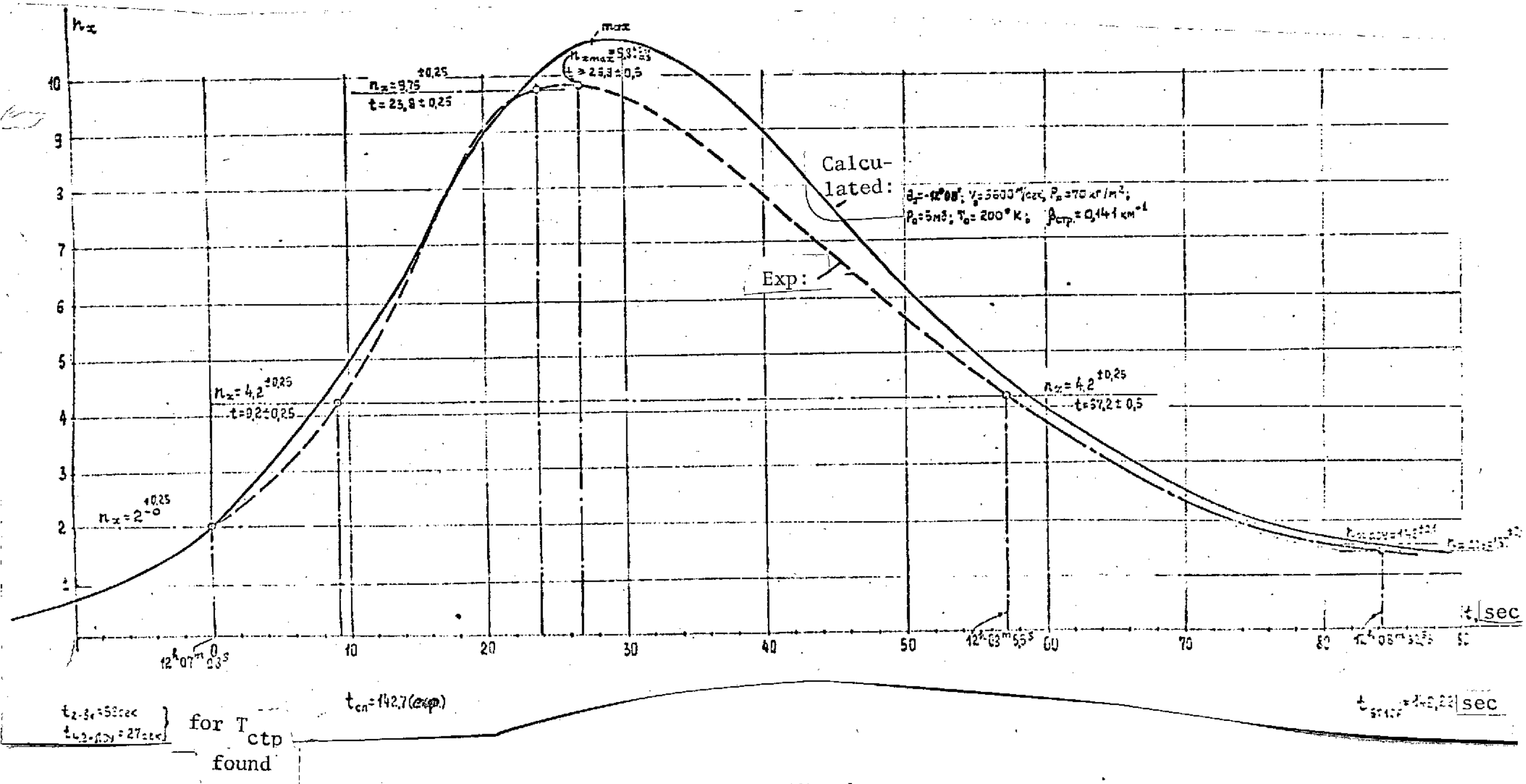
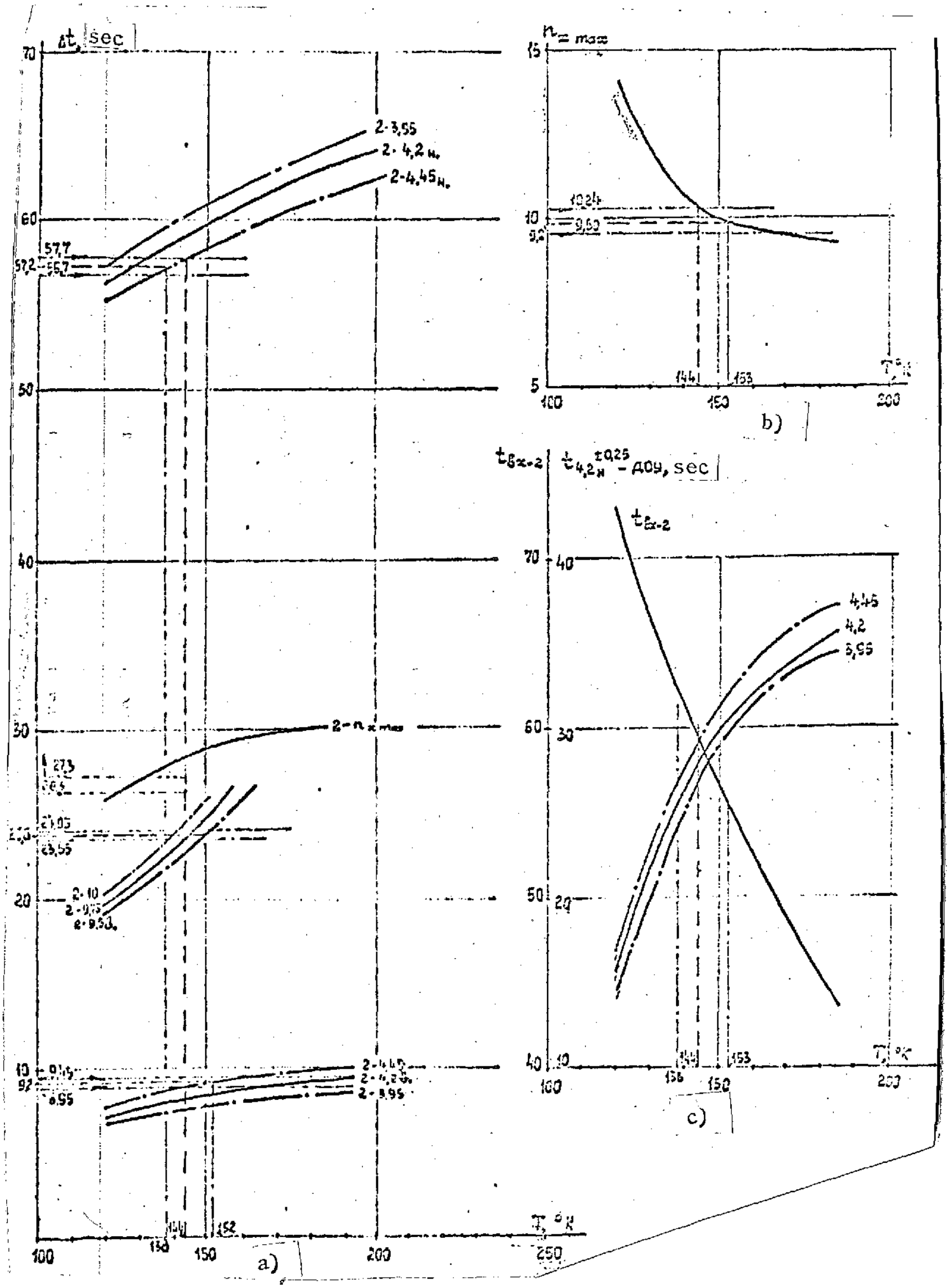



Figure 4. Change in Acceleration $n_x$ as a Function of Time

culation of Time Intervals to Moments
or Attainment of Fixed Accelerations in Comparison with
Measurement Data



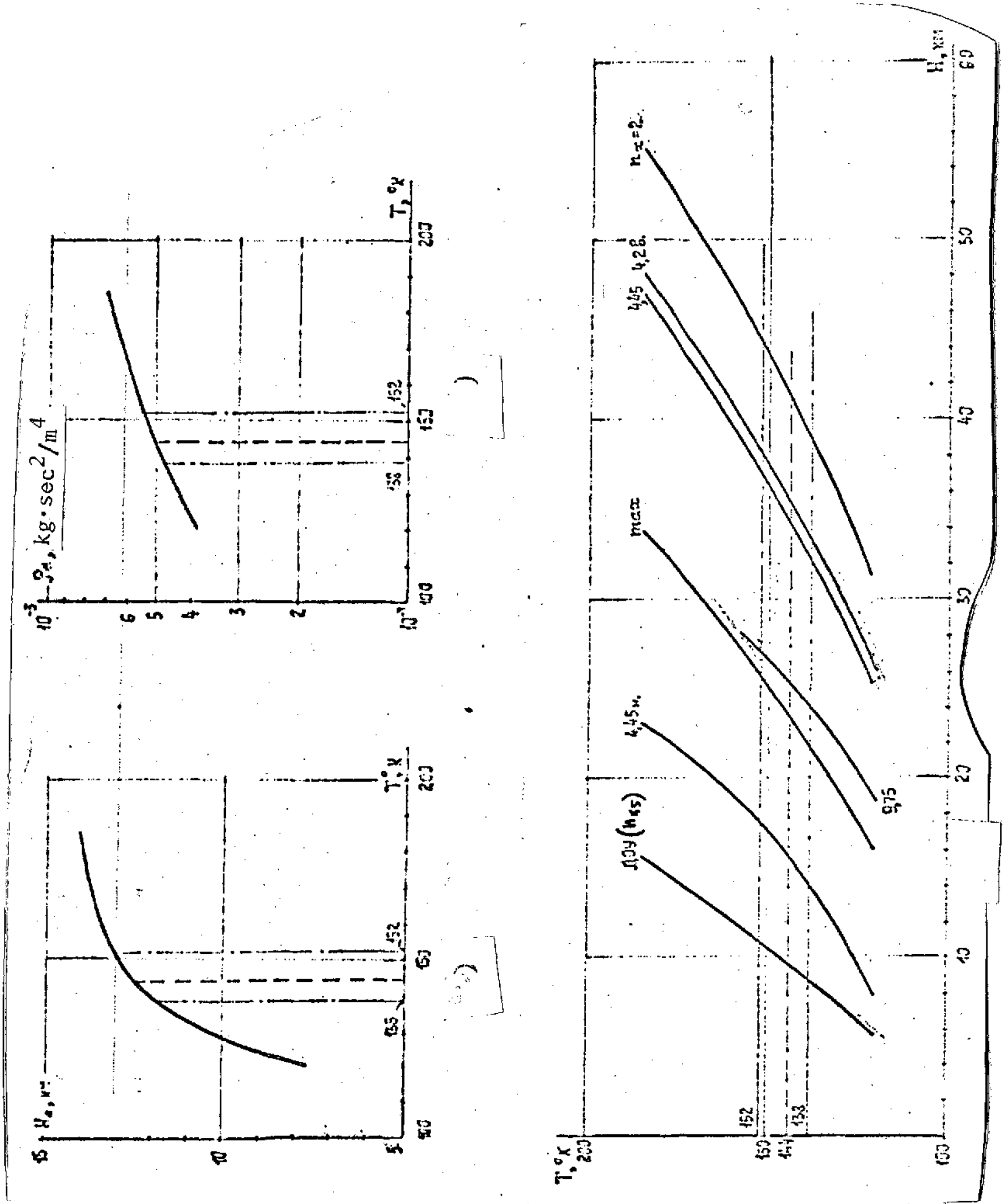
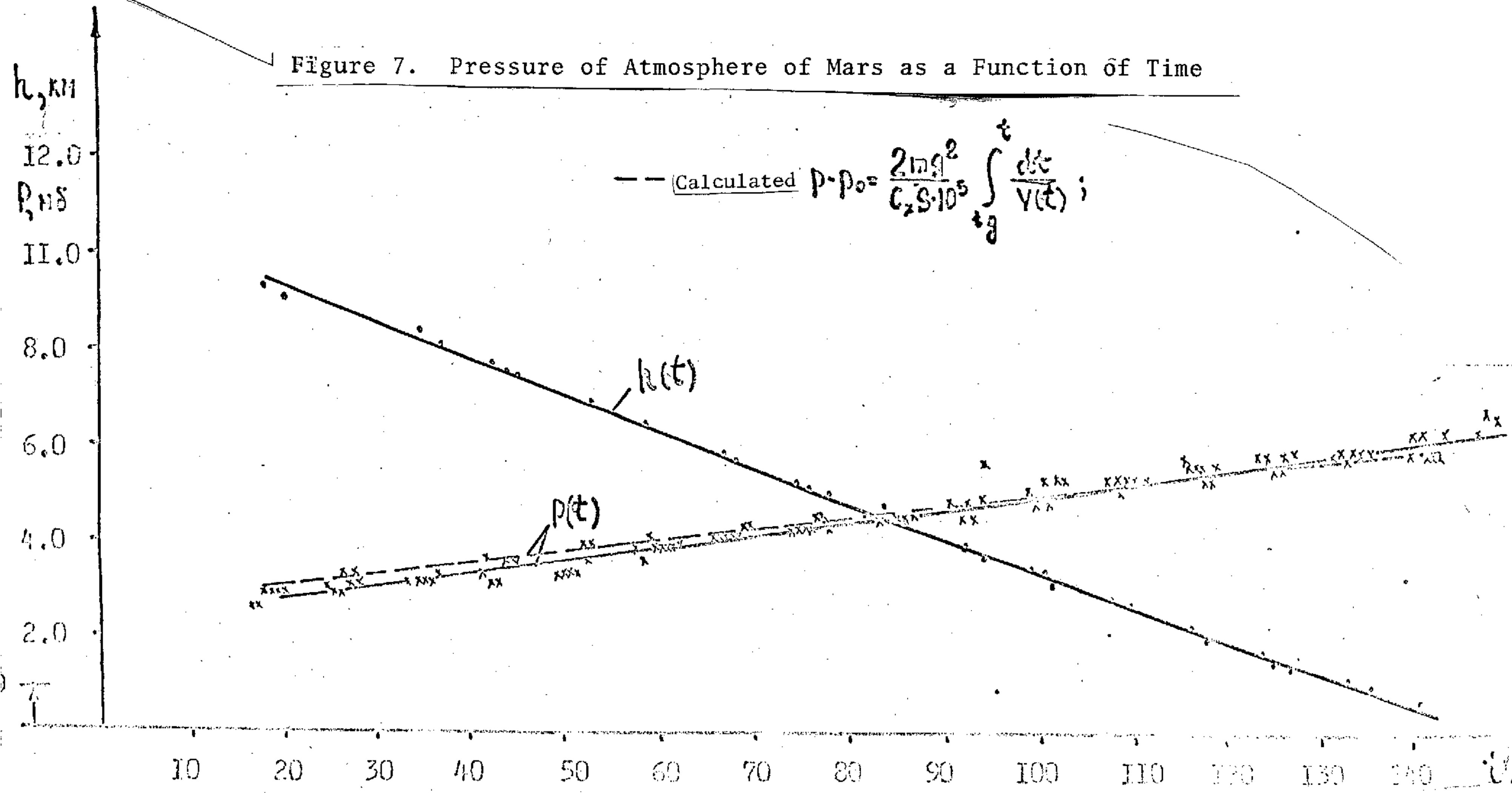



Figure 6. Estimates of Level of $n_t$ and Density $\rho_{h_t}$ for Mean Stratosphere Temperature T = 144 K (a, b) and Estimation of Altitude over Surface with Corresponding Values of $n_x$ (for 5- Millibar Model of Atmosphere), (c)

Figure 7. Pressure of Atmosphere of Mars as a Function of Time



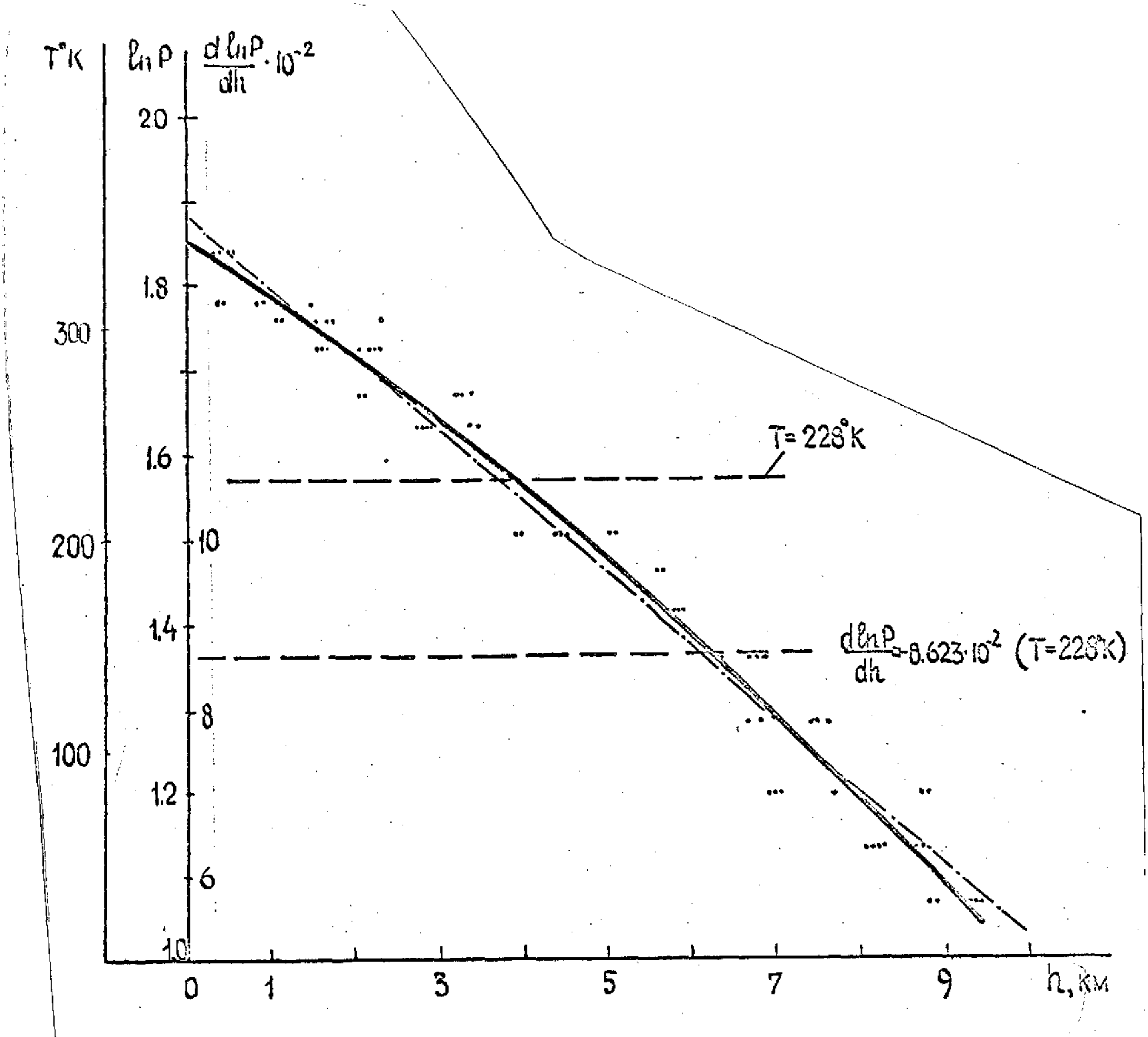



Рис. 8.а

Figure 8.a, Change in Pressure and Pressure Gradient in Atmosphere of Mars with Altitude. Estimate of Mean Temperature of Atmosphere

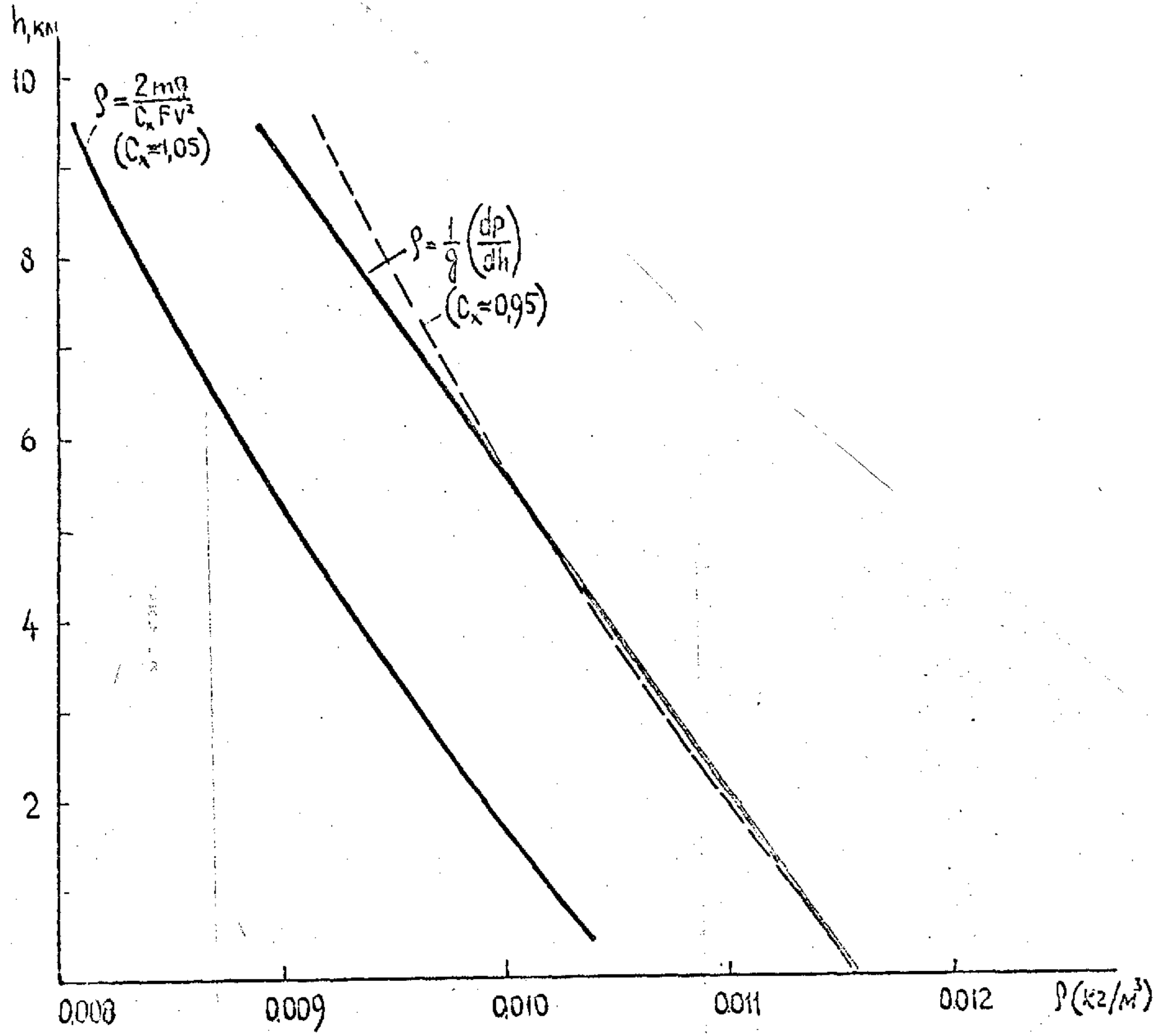



Figure 8. b, Change in Calculated Density with Altitude.

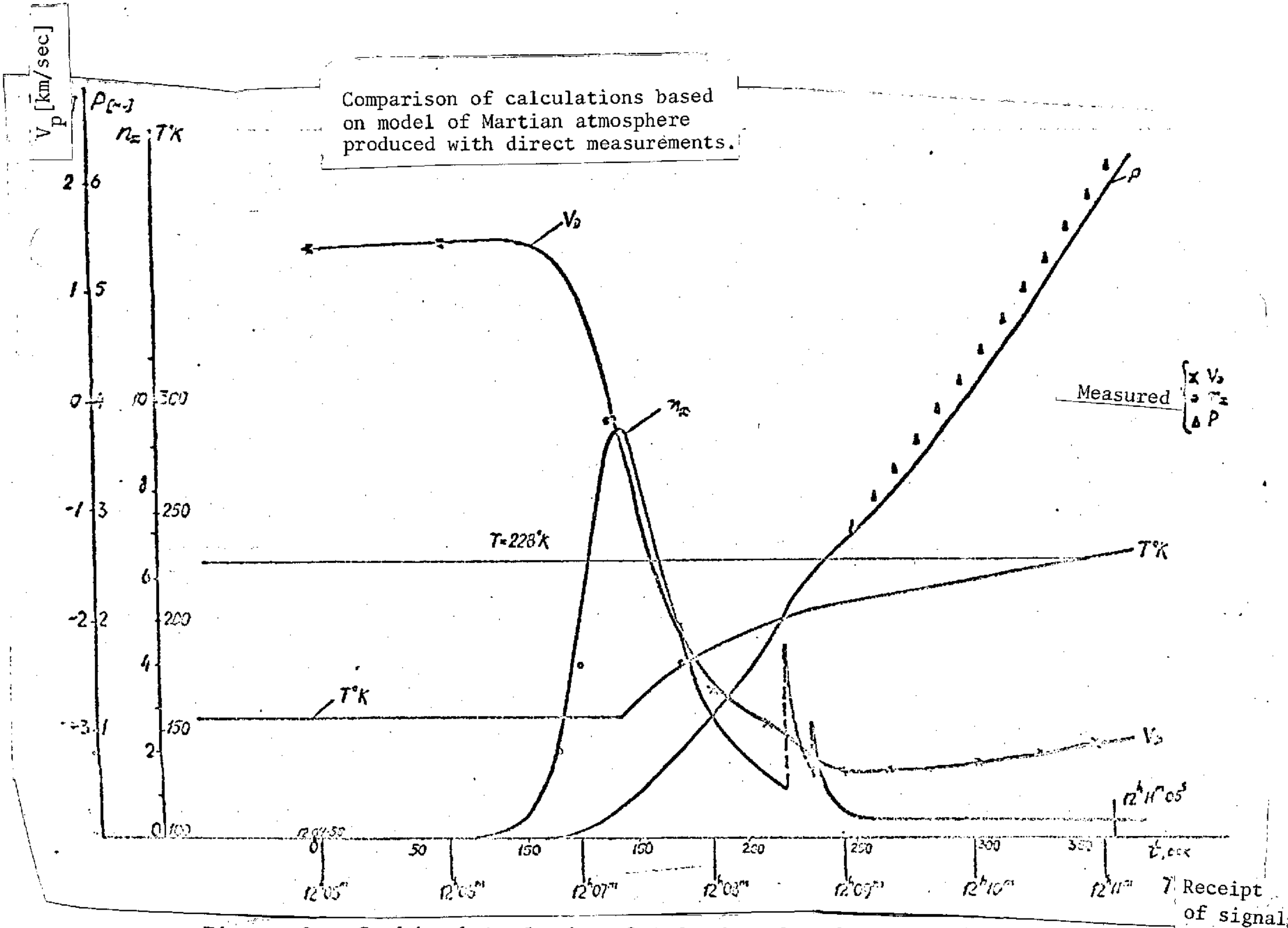



Figure 9. Combined Analysis of Calculated and Measured Values for Descent Sector of Mars-6 Spacecraft.

Figure 10. Model of Atmosphere of Mars Satisfying Combined Measurement Data During Descent Section of Mars-6 Spacecraft in Comparison with Other Models